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LASER MIXING PROCESSES

(Turbulence and Shear Layers in High Energy Lasers)

FINAL SCIENTIFIC REPORT
AFOSR Grant #77-3450
(July 1, 1977 to October 31, 1978)

David A. Russell
University of Washington

Introduction

The high energy laser was made possible by the application of high speed fluid flow to basic molecular processes. The flow is used to remove waste heat, to provide a high mass flow for compactness and a high total pressure for gas recovery, to enhance lasing through reduced cavity temperatures, and to drop the density and thus the flow uniformity necessary for beam quality. Further, it is the rapid expansion of the plenum gas that provides non-equilibrium energy for the gasdynamic laser (GDL), and provides fast mixing and upstream isolation for the chemical supersonic diffusion laser (SDL). Thus, the 20-50 kw/kgm/sec output of modern high energy lasers is integrally tied to the development of a new class of fluid flows involving non-equilibrium/reacting gases in a radiation-extraction cavity. High flow quality is essential if the laser beam is not to be degraded, and the wave systems, wakes, mixing layers, turbulence levels, and wall layers must be understood and controlled. Consideration must be given to combustion processes in plenums and mixing layers, heat transfer in the expansion nozzles, aerodynamic beam-extraction windows, and downstream recovery of the working fluid to

ambient conditions, in addition to the obvious concerns of efficiency and size. There are thus many reasons why future laser possibilities are often paced by fluid dynamics.

The Air Force Office of Scientific Research has supported a continuing program of experimental and theoretical study of the fluid dynamics of high energy lasers at the University of Washington. Three review articles, two papers on simulation facilities, a paper on a new approach to GDL expansions, and three related theses were produced under a preceding grant[1]. A number of ideas for improving laser performance were explored analytically and experimentally. Grant-related study also made possible the preparation and delivery of a professional-society-sponsored short course on GDLs, as well as an industry-sponsored course on SDLs, and additional invited lectures.

The present grant has continued these activities. Three papers were delivered[2,3,4], a thesis prepared in rough draft form[5], and an abstract prepared for an international symposium[6]. In addition, a professional-society invited-paper-session on the fluid dynamics of high power lasers was organized and chaired[7], there was an active participation in the planning of the first conference on this topic[4], and four additional invited lectures were given. Finally, a new professional-society-sponsored short course on high power lasers and their application was prepared and presented. These various activities attest to the growing importance of laser fluid dynamics, and to a recognition of the contributions of the AFOSR-sponsored program at the University of Washington to this fascinating and complicated area of fluid flow.

Research Activities

A. Mixing of Waves from Expansion Processes. Many high power lasers feature gas expansions through an array of supersonic nozzles. The flow emerges from each nozzle in a divergent condition, and is constrained by the flow in adjacent nozzles to turn through shocks originating at the nozzle exits. A decaying shock pattern is thus initiated in the downstream flow. This is particularly prominent when large angle wedge or conical expansions are used, and it has been found to be unavoidable with contoured nozzle arrays due to tip strength and/or base flow considerations. Until now the only solution for the wave system has been a 2-D development of sonic boom theory applicable to the far field. From both optical and flow process considerations there has been a growing need to verify the predicted inverse decay rate with distance, ascertain the effective origin of the decay for moderate expansion angles, solve for the near field properties, and most importantly, obtain 3-D solutions.

For simplicity, the gas exiting from the nozzles has been treated in the present study as having an effective source-like origin, the limitations on this assumption being checked by method-of-characteristic calculations. A rigorous analytical solution to the 2-D problem based on velocity and density perturbations to first and second order in the expansion angle was then developed. The flow field was divided into cells by the wave system, and the invariance of the tangential velocity across each wave used to systematically solve for the shape of the shock and the perturbation coefficients. The solutions are valid in the near field within the limits of isentropic flow, and are rendered uniformly valid in the far field by adjusting the perturbation scheme. Results are found to fare

smoothly into the far-field solution, and to show important displacements of that solution. Strong shock solutions in 2-D have been developed around a wedge-like flow assumption. These show good agreement with the perturbation solution in the near field, even for moderate expansion angles, and excellent agreement with full method-of-characteristics calculations. It is interesting to note that the flow never recovers from the relatively large wake-axis entropy production at the first turning shock in large angle cases, and thus a shear is introduced which may dominate wake effects.

An analysis of axially symmetric geometry would be difficult as Mach reflection is required by the boundary conditions on the axis of symmetry. However, it turns out that a closely packed 3-D array of nozzles has a basic hexagonal symmetry, and the flow is geometrically similar in any triangular section formed by joining the corners of a hexagon to its center. Further, each triangle has a central plane of symmetry and the essential problem is thus that of radial flow into a duct with a 30° right triangle cross section. A shock system initiates when the radial flow first turns to meet the constraint imposed by the outer plane, and this wave reflects back and forth down the duct. There is, however, another boundary condition to be met immediately at the 60° corner. This is handled by a weaker wave originating at the corner and reinforced along the intersection of the first wave system with the angled side of the duct. This second shock system essentially reflects back and forth transverse to the first. The perturbation analysis for this geometry proceeds in a similar fashion to the 2-D case, and to first order yields remarkably simple results. By keeping careful track of the hexagonal multi-shock geometry, optical-axis density-perturbation

integrations have been performed which have yielded excellent agreement with results from earlier experiments.

The basic mathematical development of this work has been reported(3,5), as has a discussion of its application(4,5), and an update on the experimentation(2).

B. <u>Mixing in Reacting Cavity Flows</u>. In the SDL, adjacent nozzles expand oxidizer and fuel-bearing streams which subsequently diffuse into each other and react exothermically to produce a population inversion among the vibrational states of the reactant. Early models merely followed the chemistry in a premixed gas, the flow entering only as a uniform translation. The process actually involves fluid mechanical considerations such as the waves just discussed, boundary layer/wake effects, base region flow and area relief, shear-layer mixing phenomena, and reaction shocks (waves from the heat release). These are complex, interactive with each other and the chemistry, and important to an understanding of the laser.

Extensive modeling has been carried out in order to clarify the influence of these effects on the HF chemical system. Typically, the real expansion effects are instantaneously mixed in to obtain uniform states at each nozzle exit. The uniform fuel and oxidizer streams are then brought together in a move-mix reacting layer that is assumed to grow at a specified rate into each stream. In each step gas is intercepted from the streams, uniformly mixed, and the chemistry turned on so that species concentration and heat release can be found at the next step. Adjustment to the external flow conditions may be incorporated as well. Both the cold and hot HF reactions are considered, with a two-level lasing system in which the excited HF is deactivated by collisions with its ground state, with atomic fuel and oxidizer, and with diluent.

A shock/Ludwieg tube facility has been developed for the study of SDL flows. Here, F_2/diluent mixtures are dissociated by the reflected shock in a 5x20 cm cross section shock tube and fed through an array of nozzles to a 5x20 cm cross section cavity. A signal from the double diaphragm initiating this flow activates a diaphragm cutter holding back a H_2/diluent mixture in a 7.5 cm Ludwieg tube. This gas feeds through alternate rows of nozzles to the same cavity. The facility produces a brief (< 1 millisecond) repeatable hot oxidizer flow within a longer period of cold fuel flow.

Pressure instrumentation in the cavity has shown rapid mixing with large effects due to combustion. There is a significant effect of base area and the pressure and degree of mixing and chemistry assigned to that region. The emphasis in the work has been on experimentation designed to explore the validity of the models and direct their improvement, establishing the importance of the various fluid effects and looking for new insight into the control of this type of process. It is intended to report preliminary findings in the near future with a Ph.D. thesis and a paper presented at an international symposium[6].

C. Mixing in Recovery Flows. The diffuser is still the largest assembly in a modern GDL, and there has been a continuing interest in reducing its volume. The principal feature of supersonic diffusers is the complex multiple-shock boundary-layer interaction region wherein the flow is converted from a supersonic to a subsonic condition. The length of this region increases with the ratio of the incoming boundary-layer thickness to the pocket height, starting with a zero-length normal shock when no boundary layer is present. In the

parallel pocket diffuser, it is thus the side wall channels that are critical to minimizing overall diffuser length. Thus, an analytical and experimental study has been carried out of the flow in rectangular ducts with thick entering boundary layers and various inlet and outlet configurations. Attention was directed to determining the channel height which gives minimum length for a specified boundary layer and recovery efficiency.

Control volume calculations were made wherein a turbulent flat plate boundary-layer was mixed with external flow to a uniform state, both in the absence of wall shear and with a choked exit caused by wall shear. The equations were solved algebraically to yield pressure recovery and choking limits as a function of external flow and boundary-layer to channel height ratios. Recovery is less than that provided by a normal shock in the free stream, and it will thus be ncessary to accomplish some geometric diffusion and/or energization if normal shock recovery is required to balance the center pocket flow. Empirical correlations for the actual recovery process were explored as a first step to more detailed modeling.

Experiments have been carried out using the flow produced by a 7.5x10 cm cross section 2-D Mach-number 3 nozzle driven by either a 7.5x10 cm or 15 cm i.d. Ludwieg tube. A constant-area boundary-layer channel was used with a moveable plate that split off a diffusion passage connected to an atmospheric pressure muffler. Multiple expansion wave reflections in the Ludwieg tube provided a staircase pressure history which could bracket the condition for unstarting the diffuser channel. A thesis is being written which describes this work.

Conclusions

A prominent feature of many high-power lasers is the decaying wave system generated when the flow enters the cavity. Models developed around the geometry of this flow have given the first solutions for the near-field in 2-D and for the whole field in 3-D. Various-coupled-flow phenomena in the chemical laser have been studied with a combination shock/Ludwieg tube facility. Guided by these experiments, 1-D analysis has been extended to include the effects of geometry and flow-derived length scales. Finally, analysis and experiment of the basic recovery mechanisms in gasdynamic laser diffusers was carried out. Further work is needed on these and other mixing processes that limit and control high-energy laser systems.

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